Neutron – Mirror Neutron Oscillations: How Fast Might They Be?

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We discuss the phenomenological implications of the neutron (n) oscillation into the mirror neutron (n'), a hypothetical particle exactly degenerate in mass with the neutron but sterile to normal matter. We show that the present experimental data allow a maximal $n - n'$ oscillation in vacuum with a characteristic time τ much shorter than the neutron lifetime, in fact as small as 1 sec. This phenomenon may manifest in neutron disappearance and regeneration experiments perfectly accessible to present experimental capabilities and may also have interesting astrophysical consequences, in particular for the propagation of ultra high energy cosmic rays.

The idea that there may exist a mirror world, a hidden parallel sector of particles that is an exact duplicate of our observable world, has attracted a significant interest over the years [1, 2, 3, 4, 5, 6, 7, 8] (for reviews, see [9, 10]). Such a theory is based on the product $G \times G'$ of two identical gauge factors with identical particle contents, where ordinary (O) particles belonging to G are singlets of G', and mirror (M) particles belonging to G' are singlets of G. Mirror parity under the proper interchange of $G \leftrightarrow G'$ and the respective matter fields makes the Lagrangians of both sectors identical to each other. Such a situation can emerge e.g. in the context of $E_8 \times E_8'$ superstring theory.

Under this hypothesis, the Universe should contain along with the ordinary photons, electrons, nucleons etc., also their mirror partners with exactly the same masses. Invisible M-matter, interacting with O-matter via gravity, could be a viable dark matter candidate [7, 8, 9, 10].

Besides gravity, the two sectors could communicate by other means. In particular, any neutral O-particle, elementary or composite, can have a mixing with its M-twin. For example, kinetic mixing between ordinary and mirror photons [2] can be revealed in the ortho-positronium oscillation [4] and can be tested also with dark matter detectors [10]. Ordinary neutrinos can mix with mirror neutrinos and thus oscillate into these sterile species [3], as well as neutral pions and Kaons into their mirror partners. Such mixings may be induced by interactions between the O- and M-fields mediated by messengers like pure gauge singlets or extra gauge bosons acting with both sectors [6, 9].

In this letter we explore the mixing between the ordinary neutron n and mirror neutron n' due to a small mass term $\delta m (\overline{n}n' + \overline{n}'n)$. We show that the existing experimental data do not exclude a rather fast $n - n'$ oscillation, with a timescale $\tau = \delta m^{-1} \sim 1$ s. Such an intriguing possibility can be tested in small scale "table-top" experiments, and it can have strong astrophysical implications, in particular for ultra high energy cosmic rays.

Let us take the minimal gauge symmetry $G = SU(3) \times SU(2) \times U(1)$ for the O-sector that contains the Higgs doublet ϕ, and quarks and leptons: left $q_L = (u, d)_L$, $l_L = (\nu, e)_L$, and right u_R, d_R, e_R [11]. As usual, we assign a global lepton charge $L = 1$ to leptons and a baryon charge $B = 1/3$ to quarks. If L and B were exactly conserved then the Majorana masses of neutrinos would be forbidden and the proton would be stable.

However, L and B are not perfect quantum numbers. They are related to accidental global symmetries possessed by the Standard Model Lagrangian at the level of renormalizable couplings, which can be however explicitly broken by higher order operators cutoff by large mass scales M. In particular, the well-known D=5 operator $\mathcal{O}_5 \sim (l\phi)^2/M$ ($\Delta L = 2$), yields, after inserting the Higgs vacuum expectation value (VEV) $\langle \phi \rangle$, small Majorana masses for neutrinos, $m_\nu \sim \langle \phi \rangle^2/M$ [12], while the D=9 operators $\mathcal{O}_9 \sim (udd)^2/M^5$ or $(qqd)^2/M^5$ ($\Delta B = 2$) lead to neutron - antineutron ($n - \tilde{n}$) oscillation phenomenon [13].

Suppose now that there exists a hidden M-sector with a gauge symmetry $G' = SU(3)' \times SU(2)' \times U(1)'$, a mirror Higgs doublet ϕ', and mirror quarks and leptons: $q_L' = (u', d')_L$, $l_L' = (\nu', e')_L$ and u_R', d_R', e_R', where one assigns a lepton charge $L' = 1$ to mirror leptons and a baryon charge $B' = 1/3$ to mirror quarks. Mirror parity $G \leftrightarrow G'$ tells that all coupling constants (gauge, Yukawa, Higgs) are identical for both sectors, the O- and M-Higgses have equal VEVs, $\langle \phi \rangle = \langle \phi' \rangle$, and hence the mass spectrum of mirror particles is exactly the same as that of ordinary ones. In addition, if the O-sector contains L and B violating operators like $\mathcal{O}_5$ and $\mathcal{O}_9$, then analogous L' and B' violating operators $\mathcal{O}_5'$ and $\mathcal{O}_9'$ should be included in the M-sector.

Moreover, there can exist higher order operators that couple gauge singlet combinations of O- and M-particles.

In particular, the D=5 operator

$$\mathcal{O}_5^{\mathrm{mix}} \sim \frac{1}{M}(l\phi)(l'\phi') \tag{1}$$

induces the mixing between the ordinary and mirror neutrinos [3], and the D=9 operators coupling three ordinary and three mirror quarks,

$$\mathcal{O}_9^{\mathrm{mix}} \sim \frac{1}{\mathcal{M}^5}(udd)(u'd'd') + \frac{1}{\mathcal{M}^5}(qqd)(q'q'd') , \tag{2}$$

result in ordinary neutron - mirror neutron mixing. On the other hand, if one postulates conservation of the combined quantum number $\bar{B} = B - B'$, the operators $\mathcal{O}_9, \mathcal{O}_9'$ are forbidden while the operator $\mathcal{O}_9^{\mathrm{mix}}$ is allowed. Hence, the exact $\bar{B}$ conservation would suppress the $n - \tilde{n}$ oscillation but not the $n - n'$ oscillation [14]. Taking into account that the matrix elements of the operators (2) between the neutron states are typically $\sim 10^{-4}$ GeV^6, one estimates the mass mixing term between n and n' states as:

$$\delta m \sim \left(\frac{10\,\mathrm{TeV}}{\mathcal{M}}\right)^5 \times 10^{-15}\,\mathrm{eV} . \tag{3}$$

One could naively think that the bound on $n-n'$ mixing is nearly as strong as the one on $n - \tilde{n}$ mixing: $\delta m_{n\tilde{n}} < 10^{-23}$ eV, or $\tau_{n\tilde{n}} = \delta m_{n\tilde{n}}^{-1} > 10^8$ s, which follows from the direct experimental search of free neutron oscillation into antineutron ($\tilde{n}$) [15], as well as from the limits on nuclear stability: a stable nucleus (A, Z) would decay into states $(A - 2, Z)$ or $(A - 2, Z - 1)$ due to the conversion $n \to \tilde{n}$ followed by $\tilde{n}n$ or $\tilde{n}p$ annihilation into pions with a total energy of nearly two nucleon masses [16]. However, we show below that the bound on $n - n'$ oscillation is many orders of magnitude weaker, $\tau = \delta m^{-1} > 1$ s. This indeed is quite surprising! The $n-n'$ oscillation time can be much smaller than the neutron lifetime $\tau_n \simeq 10^3$ s.

As far as mirror neutrons are invisible, the $n - n'$ oscillation can manifest experimentally only as a neutron disappearance. If $\tau \ll \tau_n$, strictly free neutrons would oscillate many times with a maximal mixing angle ($\theta = 45°$) before they decay. Thus, instead of the exponential law $P(t) = \exp(-t/\tau_n)$ for the neutron survival probability, one would observe the oscillating behaviour $P(t) = \cos^2(t/\tau)\exp(-t/\tau_n)$. Is not this immediately excluded by the experiments measuring the neutron lifetime with great accuracy? The answer is no! Simply because in these experiments neutrons and mirror neutrons are subject to very different conditions.

The evolution of free non-relativistic neutrons is described by the effective Hamiltonian in $n - n'$ space,

$$H = \begin{pmatrix} m - i\Gamma/2 - V & \delta m \\ \delta m & m - i\Gamma/2 - V' \end{pmatrix} , \tag{4}$$

where m is the neutron mass and $\Gamma = 1/\tau_n$ its decay width, which, due to exact mirror parity, are precisely the same

for mirror neutrons. However, the potentials V and V' felt by n and n' are not quite the same. Namely, since the experiments are done on Earth, the terrestrial magnetic field, $B \simeq 0.5$ G, induces an effective contribution $V = \mu B \simeq 3 \times 10^{-12}$ eV, where μ is the neutron magnetic moment. On the other hand, $V' = 0$ as far as no mirror magnetic fields exist on Earth. Thus, for $\delta m \ll V$, the effective mixing angle between n and n' states is $\theta_{\mathrm{eff}} \approx \delta m/V$ while the oscillation time is $\tau_{\mathrm{eff}} \approx 2/V \simeq 4 \times 10^{-4}$ s, and hence the average transition probability becomes $\bar{P}_{nn'} \simeq 2\,(\delta m/V)^2$. For example, for $\delta m = 10^{-15}$ eV one has $\bar{P}_{nn'} \approx 2 \times 10^{-7}$, and such a small disappearance effect could hardly be observed in the experiments. Thus, to improve the experimental sensitivity the magnetic field should be suppressed.

In the ILL-Grenoble experiment designed to search for neutron - antineutron oscillation, the magnetic field was reduced to $B \sim 10^{-4}$ G [15]. Cold neutrons propagated in vacuum with an average speed of 600 m/s and effective time of flight $t \simeq 0.1$ s, in a μ-metal vessel shielding the magnetic field. No antineutrons were detected and the limit $\tau_{n\tilde{n}} > 0.86 \times 10^8$ s was reported. Clearly, the search for $n - n'$ oscillation was not the aim of this experiment, but it can be used to set a crude limit on the timescale τ. For τ larger than the neutron propagation time $t \simeq 0.1$ s, the oscillation probability is $P_{nn'}(t) \approx (t/\tau)^2$. By monitoring the neutron beam intensity it was observed that about 5% of neutrons disappeared [15]. If this deficit could be entirely due to $n-n'$ oscillation, this would imply $\tau \approx 0.45$ s. However, as far as most of the losses can be attributed to scatterings with the walls in the drift vessel, one can assume rather conservatively that no more than 1% of losses were due to $n - n'$ oscillation, and thus obtain a bound $\tau > 1$ s, or $\delta m < 10^{-15}$ eV.

Let us discuss whether the bounds from nuclear stability, which give the strongest limit on $\tau_{n\tilde{n}}$, are applicable also to the case of $n - n'$ oscillation. One may naively think that it could destabilize nuclei as follows: in a stable nucleus (A, Z) (e.g. ^{16}O) n oscillates into n'. Then n', or its β-decay $n' \to p'e'\tilde{\nu}'_e$ products, can escape from the nucleus thus producing an unstable isotope $(A - 1, Z)$ (^{15}O) whose characteristic signals could be seen in large volume detectors as e.g. Superkamiokande.

This kind of reasoning certainly applies to neutron invisible decay channels, e.g. $n \to 3\nu$. However, it is invalid for the $n - n'$ oscillation channel as far as the mirror particles n', p', e' are exactly degenerate in mass with their ordinary partners n, p, e. Indeed, energy conservation allows the decay $(A, Z) \to (A - 1, Z) + n'$ (or $+p'e'\tilde{\nu}'_e$) only if the mass difference between the isotopes (A, Z) and $(A - 1, Z)$ is larger than m_n (or $m_p + m_e$). But then also the decay with neutron emission ($p\,e\,\tilde{\nu}_e$ emission) would be kinematically allowed and such a nucleus could not be stable. One confirms by inspection that all nuclear ground states satisfying such conditions have short lifetimes rendering the

extremely rare mirror channels invisible in practice [17].

Thus, the $n - n'$ oscillation cannot destabilize nuclei and so the only realistic limit remains $\tau > 1$ s imposed by the data from the Grenoble experiment [15].

We discuss now the possible theoretical models for the operators (2) and their phenomenological implications. The contact terms of the form $\mathcal{O}_9^{\mathrm{mix}}$ with $\mathcal{M} \sim 10$ TeV, if valid at TeV energies, could have interesting consequences for future high energy colliders as the LHC. Namely, the mirror baryons could be produced in proton collisions, which would be seen as processes with baryon number violation and large missing energy.

For example, in theories with large extra dimensions [18], the ordinary and mirror worlds can be conceived as parallel 3-dimensional branes embedded in a higher dimensional space, where O-particles with a gauge group G are localized on one brane and M-particles with a gauge group G' on another brane, while gravity propagates in the bulk. In the context of such a theory, operators $\mathcal{O}_9^{\mathrm{mix}}$ with a cutoff $\mathcal{M} \sim 10$ TeV could be induced as effects of the TeV scale quantum gravity. In addition, the baryon number can be related to a gauge symmetry in the bulk [18], in our case $U(1)_{\bar{B}}$, $\bar{B} = B - B'$, that forbids the operators $\mathcal{O}_9$, $\mathcal{O}_9'$ leading to $n - \tilde{n}$ oscillations.

It is also possible that at TeV energies the terms (2) do not exist literally in the contact form, but are rather induced in the context of some renormalizable theory. Let us give a simple example of such a model. Assuming again $\bar{B}$ conservation, consider the Yukawa terms

$$ udS + qqS + S^*d\mathcal{N} + u'd'S' + q'q'S' + S'^*d'\mathcal{N}' \qquad (5) $$

where S ($\bar{B} = -2/3$) is a color-triplet scalar S with mass M_S, having precisely the same gauge quantum numbers as the right down-quark $d_{(R)}$, and S' ($\bar{B} = 2/3$) is its mirror partner with the same mass M_S, whereas $\mathcal{N}_{(R)}$ ($\bar{B} = -1$) and $\mathcal{N}'_{(R)}$ ($\bar{B} = 1$) are additional gauge singlet fermions, with a large mass term $\tilde{M}\mathcal{N}\mathcal{N}'$ (for simplicity, the Yukawa constants are assumed to be of order 1). Then, at energies $E \ll M_S, \tilde{M}$, the operators $\mathcal{O}_9^{\mathrm{mix}}$ are induced with a cutoff scale $\mathcal{M} \simeq (M_S^4 \tilde{M})^{1/5}$ (see Fig. 1) [19].

If e.g. both M_S and $\tilde{M}$ are ~ 10 TeV, then at TeV energies the operators (2) act in a contact form. The scale $\mathcal{M} \sim 10$ TeV can be effectively obtained on other extremes,
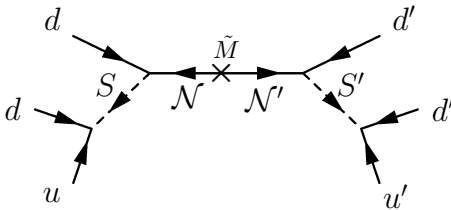

FIG. 1: Diagram inducing neutron - mirror neutron mixing.

by taking e.g. $M_S \sim 200$ GeV and $\tilde{M} \sim 6 \times 10^{10}$ GeV, or $M_S \sim 700$ GeV and $\tilde{M} \sim 4 \times 10^8$ GeV. In this case, while the detection of the scalar S is within the reach of LHC, the mirror quarks cannot be produced as the messengers $\mathcal{N}$, $\mathcal{N}'$ are far too heavy.

Let us address now the cosmological limits. The most serious constraints come from the requirement that the O- and M-worlds should have different temperatures T and T' at the Big Bang Nucleosynthesis (BBN) epoch. The mirror sector would contribute to the universe expansion rate as an effective number of extra neutrinos $\Delta N_\nu \simeq 6.14 \, (T'/T)^4$ [5], and thus the bounds on ΔN_ν demand that $T' < 0.5\,T$ or so. This can be achieved by adopting the following paradigm [9]: at the end of inflation the O- and M-worlds are (re)heated in a non symmetric way, $T_r > T'_r$, which can naturally occur in the context of certain inflationary models; after (re)heating, $T < T_r$, the processes between O- and M-particles are too slow to bring the two sectors in equilibrium, so that both systems expand adiabatically, maintaining the temperature asymmetry $T' < T$ in all subsequent epochs.

The operators (2) induce collision processes as $udd \to \bar{u}'\bar{d}'\bar{d}'$, etc. that cause entropy transfer between the ordinary and mirror sectors. Their effective rate scales as $\Gamma = A\,T^{11}/\mathcal{M}^{10}$, where the coefficient $A \sim 0.06$ accounts for phase space factors, and for $\mathcal{M} \sim 10$ TeV they would be in equilibrium at temperatures above $T_{\mathrm{eq}} \sim 0.5$ TeV or so. Thus, in order to fulfill the BBN request on the $T' < T$ asymmetry, the (re)heat temperature T_r should be smaller than 0.5 TeV [20].

This applies only if at temperatures $T \sim T_{\mathrm{eq}}$ the operators (2) act in the contact form. In the context of the model presented above, that is true if the scalar S is heavy enough, $M_S > 0.5$ TeV or so. For smaller M_S, however, the dominant process at temperatures $T > M_S$ would be rather $d\tilde{S} \to \bar{d}'S'$. Comparing its rate $\Gamma \simeq 10^{-2} T^3/\tilde{M}^2$ with the Hubble parameter $H = 1.7\,g_*^{1/2}T^2/M_{\mathrm{Pl}}$ ($g_* \sim 10^2$), one obtains that these processes would bring the two sectors in equilibrium only at temperatures above $T_{\mathrm{eq}} \sim 2 \times 10^3 \, \tilde{M}^2/M_{\mathrm{Pl}}$, i.e., $T_{\mathrm{eq}} \sim 2 \times 10^3 \, \mathcal{M}^{10}/(M_S^8 M_{\mathrm{Pl}}) \sim 0.5$ TeV $\times (0.5$ TeV$/M_S)^8$.

Hence, the output of the limit $T_r < T_{\mathrm{eq}}$ strongly depends on M_S. For $M_S < 0.5$ TeV it is milder: e.g. for $M_S \sim 200$ GeV ($\tilde{M} \sim 6 \times 10^{10}$ GeV) it turns $T_r < 6 \times 10^5$ GeV. But it sharply strengthens with increasing M_S, and for $M_S > 0.5$ TeV becomes roughly $T_r < 0.5$ TeV. This restricts the possible inflation scenarios and excludes many popular scenarios for primordial baryogenesis.

But on the other hand, the same particle exchange processes between O- and M-sectors, $udd \to \bar{u}'\bar{d}'\bar{d}'$ or $d\tilde{S} \to \tilde{d}'S'$, once they are out of equilibrium, violate B, B' and possibly also CP, could provide a plausible low-temperature baryogenesis mechanism for both observable matter (O-baryons) and dark matter (M-baryons), along the lines of the leptogenesis scheme via the scatterings

$l\phi \to \bar{l}'\bar{\phi}'$ suggested in [7, 9].

The fast $n - n'$ oscillation could have intriguing implications for ultra high energy (UHE) cosmic rays. Namely, when a UHE proton p scatters a relic photon, it produces a neutron n that promptly oscillates into a mirror neutron n' which then decays into a mirror proton p'. The latter undergoes a symmetric process, scattering a mirror relic photon and producing back an ordinary nucleon. However, as the M-sector is cooler, $T'/T < 0.5$, the mean free path of p' is larger by a factor of $(T/T')^3$ than that of ordinary protons (~ 5 Mpc). In this way, the UHE protons could propagate at large cosmological distances without significant energy losses. This may relax the Greisen-Zatsepin-Kuzmin cutoff in the cosmic ray spectrum [21] and also explain the correlation between the observed UHE protons and far distant sources as BL Lacertae [22].

Concluding, we observed an intriguing loophole in the physics of such a familiar and long studied particle as the neutron: the existing experimental data do not exclude that its oscillation time into a mirror partner may be as small as 1 s. This oscillation, however, is impossible for neutrons bound in nuclei, while for free neutrons it is suppressed by matter and magnetic field effects [23].

Our suggestion is falsifiable at small costs. "Table-top" experiments searching for neutron disappearance ($n \to n'$) and regeneration ($n \to n' \to n$), performed in proper "background-free" conditions, may discover the neutron - mirror neutron oscillation and thus reveal the existence of sterile partners of nucleons, opening up a window to the mirror world with a number of serious implications in astrophysics and cosmology.

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[1] T.D. Lee and C.N. Yang, Phys. Rev. **104**, 254 (1956); I.Yu. Kobzarev, L.B. Okun and I.Ya. Pomeranchuk, Sov. J. Nucl. Phys. **3**, 837 (1966); M. Pavšič, Int. J. Theor. Phys. **9**, 229 (1974); S.I. Blinnikov and M.Yu. Khlopov, Sov. Astron. **27**, 371 (1983); E. Kolb, D. Seckel and M. Turner, Nature **314**, 415 (1985).

[2] B. Holdom, Phys. Lett. B **166**, 196 (1986); S.L. Glashow, Phys. Lett. B **167**, 35 (1986); E.D. Carlson and S.L. Glashow, Phys. Lett. B **193**, 168 (1987); R. Foot, H. Lew and R.R. Volkas, Phys. Lett. B **272**, 67 (1991).

[3] R. Foot, H. Lew and R.R. Volkas, Mod. Phys. Lett. A **7**, 2567 (1992); E.K. Akhmedov, Z.G. Berezhiani and G. Senjanović, Phys. Rev. Lett. **69**, 3013 (1992); R. Foot and R.R. Volkas, Phys. Rev. D **52**, 6595 (1995); Z.G. Berezhiani and R.N. Mohapatra, Phys. Rev. D **52**, 6607 (1995). Z.K. Silagadze, Phys. At. Nucl. **60**, 272 (1997).

[4] S. Gninenko, Phys. Lett. B **326**, 317 (1994); R. Foot and S. Gninenko, Phys. Lett. B **480**, 171 (2000); A. Badertscher et al., Int. J. Mod. Phys. A **19**, 3833 (2004).

[5] Z. Berezhiani, A. Dolgov and R.N. Mohapatra, Phys. Lett. B **375**, 26 (1996); Z.G. Berezhiani, Acta Phys. Pol. B **27**, 1503 (1996).

[6] Z. Berezhiani, Phys. Lett. B **417**, 287 (1998).

[7] L. Bento and Z. Berezhiani, Phys. Rev. Lett. **87**, 231304 (2001); Fortsch. Phys. **50**, 489 (2002); R. Foot and R.R. Volkas, Phys. Rev. D **68**, 021304(R) (2003).

[8] Z. Berezhiani, D. Comelli and F.L. Villante, Phys. Lett. B **503**, 362 (2001); A. Ignatiev and R.R. Volkas, Phys. Rev. D **68**, 023518 (2003); Z. Berezhiani et al., Int. J. Mod. Phys. D **14**, 107 (2005).

[9] Z. Berezhiani, Int. J. Mod. Phys. A **19**, 3775 (2004).

[10] R. Foot, Int. J. Mod. Phys. A **19**, 3807 (2004).

[11] For simplicity, we omit the gauge, spinor and family indices. In the following, whenever there is no ambiguity, the chiral symbols L and R are omitted as well. Antiparticles will be marked as $\tilde{p}, \tilde{n}$, etc..

[12] S. Weinberg, Phys. Rev. Lett. **43**, 1566 (1979).

[13] V.A. Kuzmin, JETP Lett. **12**, 228 (1970); S.L. Glashow, Proceedings of Neutrino'79, Bergen, Norway, 1979, edited by A. Haatuft and C. Jarlskog (University of Bergen, Bergen, 1980), Vol. 1, p. 518; R.N. Mohapatra and R.E. Marshak, Phys. Rev. Lett. **44**, 1316 (1980).

[14] If the Majorana operators $\mathcal{O}_5, \mathcal{O}_5'$ are also forbidden by $\bar{L} = L - L'$ conservation, then $\mathcal{O}_5^{\text{mix}}$ yields light Dirac neutrinos with masses $m_\nu \sim \langle\phi\rangle^2/M$, where the right-handed components are mirror anti-neutrinos: $\nu_R' = \nu_L'^{\,c}$.

[15] M. Baldo-Ceolin et al., Z. Phys. C **63**, 409 (1994).

[16] K.G. Chetyrkin et al., Phys. Lett. B **99**, 358 (1981).

[17] In principle, the $n - n'$ mixing could destabilize also objects like neutron stars. However, the effective mixing angle is suppressed by the neutron Fermi energy of several MeV, $\theta_{\text{eff}}^2 < 10^{-44}$, and one can easily estimate that the conversion time into a mirror neutron star exceeds by many orders of magnitude the age of the Universe.

[18] N. Arkani-Hamed, S. Dimopoulos and G. Dvali, Phys. Lett. B **429**, 263 (1998); Phys. Rev. D **59**, 086004 (1999).

[19] The $n - \tilde{n}$ oscillation can be also accommodated by including $\bar{B}$ violating mass terms $\mu(\mathcal{N}\mathcal{N} + \mathcal{N}'\mathcal{N}')$ with $\mu \ll \tilde{M}$, that give rise to the operators $\mathcal{O}_9, \mathcal{O}_9'$ cutoff by $\mathcal{M}_{n\tilde{n}}^5 \sim (\tilde{M}/\mu)\mathcal{M}^5$. Then, for $\mathcal{M} \sim 10$ TeV, the bound $\delta m_{n\tilde{n}} < 10^{-23}$ eV requires $\mu/\tilde{M} < 10^{-8}$.

[20] The $n - n'$ oscillation itself has no effect at the BBN epoch because it is strongly suppressed by matter effects.

[21] K. Greisen, Phys. Rev. Lett. **16**, 748 (1966); G.T. Zatsepin and V.A. Kuzmin, JETP Lett. **4**, 78 (1966).

[22] P. Tinyakov and I. Tkachev, JETP Lett. **74**, 1 (2001); ibid. 445 (2001); Astropart. Phys. **18**, 165 (2002).

[23] The $n - n'$ and $\nu - \nu'$ mixings induce together an effective operator $\sim G_F^2 m_\nu \delta m\,(pe)(p'e')$ that mixes the hydrogen atom H and its mirror atom H'. A larger effect may result directly from independent operators $\propto (qque)(q'q'u'e')$, etc.. The limits on the H-H' oscillation, also sensitive to matter and magnetic field effects, will be discussed elsewhere.